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CMS Collaboration ; Canelli, F ; Caminada, L ; Chiochia, V ; Kilminster, B ; Robmann, P ; et al

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Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

Results are presented of a search for heavy stable charged particles produced in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ using a data sample corresponding to an integrated luminosity of $2.5\,\text{fb}^{-1}$ collected in 2015 with the CMS detector at the CERN LHC. The search is conducted using signatures of anomalously high energy deposits in the silicon tracker and long time-of-flight measurements by the muon system. The data are consistent with the expected background, and upper limits are set on the cross sections for production of long-lived gluinos, top squarks, tau sleptons, and lepton-like long-lived fermions. These upper limits are equivalently expressed as lower limits on the masses of new states; the limits for gluinos, ranging up to 1610 GeV, are the most stringent to date. Limits on the cross sections for direct pair production of long-lived tau sleptons are also determined.

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*See Appendix A for the list of collaboration members

1 Introduction

Many extensions of the standard model (SM) include heavy long-lived charged particles that might have high momentum, but speed significantly smaller than the speed of light [1–3] and/or charge, Q, not equal to the elementary charge $\pm 1e$ [4–7]. Those particles with lifetimes greater than a few nanoseconds can travel distances larger than the size of a typical collider detector and appear quasi-stable like the pion or kaon. These particles are generally referred to as heavy stable charged particles (HSCPs) and can be singly ($|Q| = 1e$), fractionally ($|Q| < 1e$), or multiply ($|Q| > 1e$) charged. Without dedicated searches, HSCPs may be misidentified or unobserved, since charged particle identification algorithms at hadron collider experiments generally assume that particles have speeds close to the speed of light and charges of $\pm 1e$. Additionally, HSCPs may be charged during only a part of their passage through detectors, further limiting the ability of standard algorithms to identify them.

For HSCP masses greater than about 100 GeV, a significant fraction of particles produced at the LHC will have a relative velocity $\beta \equiv v/c < 0.9$. It is possible to distinguish $|Q| \geq 1e$ particles with $\beta < 0.9$ from light SM particles traveling close to the speed of light through their higher rate of energy loss via ionization ($\mathrm{d}E/\mathrm{d}x$) or through their longer time-of-flight (TOF) to the outer detectors. This paper describes a search for HSCPs using the CMS detector in two ways: (i) requiring tracks to be reconstructed only in the silicon detectors, the *tracker-only* analysis; (ii) requiring tracks to be reconstructed in both the silicon detectors and the muon system, referred to as the *tracker+TOF* analysis.

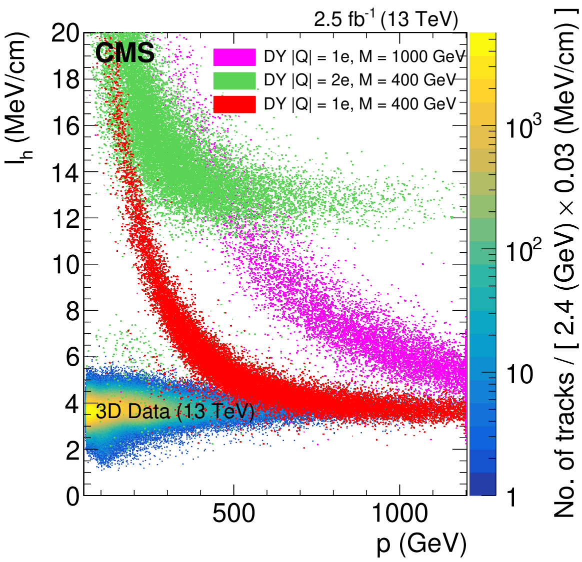

Figure 1: Distribution of the $\mathrm{d}E/\mathrm{d}x$ estimator, I_{h} (see Section 3.1), versus particle momentum for tracks in the 13 TeV data, and for simulation of HSCP for singly or multiply charged particles with masses of 400 and 1000 GeV. The vertical scale shows the density of entries for data only.

The dependence of $\mathrm{d}E/\mathrm{d}x$ on the particle momentum is described by the Bethe-Bloch formula [8]. This dependence can be seen in Fig. 1, which shows the $\mathrm{d}E/\mathrm{d}x$ estimator versus momentum for tracks from data and the generated Monte Carlo (MC) samples for HSCP signals with various charges. In the momentum range of interest at the LHC (10–1000 GeV), SM particles have nearly uniform ionization energy loss ($\approx$3 MeV/cm). Searching for candidates with larger $\mathrm{d}E/\mathrm{d}x$ gives sensitivity to massive particles with $|Q| \geq 1e$.

Previous collider searches for HSCPs have been performed at LEP [9–12], HERA [13], the Tevatron [14–17] and the CERN LHC during Run 1 (proton-proton collisions with $\sqrt{s}$ up to

8 TeV) [18–26]. The results from these searches have placed significant bounds on theories beyond the SM [27, 28], such as lower limits at 95% confidence level (CL) on the mass of long-lived gluinos (1300 GeV), top squarks (900 GeV), and directly pair-produced tau sleptons (330 GeV).

In the present paper, results of searches for singly and multiply charged HSCPs in 2.5 fb^{-1} of data collected with the CMS detector at $\sqrt{s} = 13$ TeV in 2015 are presented. Similar limits on HSCPs were recently obtained by the ATLAS experiment [29, 30] using 3.2 fb^{-1} of 13 TeV data collected in 2015.

2 Signal benchmarks

The analyses described in this paper employ several HSCP models as benchmarks, to account for a range of signatures that are experimentally accessible.

The first type of signal consists of HSCPs that interact via the strong force and hadronize with SM quarks to form R-hadrons [2, 3]. As in Ref. [26], events involving pair production of gluinos ($\tilde{\mathrm{g}}$) and top squarks ($\tilde{\mathrm{t}}_1$), with mass values in the range 300-2600 GeV, are generated according to the Split Supersymmetry (Split SUSY) scenarios [31–34]. Gluinos are generated assuming the squark mass is 10 TeV [31, 35]. PYTHIA 8.153 [36], with the underlying event tune CUETP8M1 [37], is used to generate the 13 TeV MC samples. The fraction, f, of produced $\tilde{\mathrm{g}}$ hadronizing into a $\tilde{\mathrm{g}}$-gluon state is an arbitrary value of the hadronization model. It determines the fraction of R-hadrons that are neutral at production. For this search, results are obtained for two different values of f, 0.1 and 0.5. As in Ref. [26], two scenarios of R-hadron strong interactions with nuclear matter are considered. The first scenario follows the cloud model in Refs. [38, 39], which assumes that the R-hadron is surrounded by a cloud of colored, light constituents that interact during scattering. Therefore, the R-hadron interacting inside the detector may change its charge sign. The second scenario adopts a model of complete charge suppression [40] where the R-hadron becomes a neutral particle before it enters the muon system. Both the *tracker-only* and *tracker+TOF* analyses are used to search for these signals, although only the *tracker-only* analysis is expected to have sensitivity in the charge-suppressed scenario.

The second type of signal consists of HSCPs that behave like leptons. The minimal gauge mediated supersymmetry breaking (mGMSB) model [41] is selected as a benchmark for lepton-like HSCPs. Production of quasi-stable sleptons at the LHC can proceed either directly or via production of heavier supersymmetric particles (mainly squarks and gluinos) that decay and lead to two sleptons at the end of the decay chain. This latter process is dominant because the direct production process is electroweak. Direct production is relevant only if squarks and gluinos are too heavy to be produced at the LHC. The mGMSB model is explored using the SPS7 slope [42], which has the tau slepton (stau $\tilde{\tau}_1$) as the next-to-lightest supersymmetric particle (NLSP). The particle mass spectrum and the decay table are produced with the program ISASUGRA 7.69 [43]. The mGMSB model is characterized by six fundamental parameters. The mGMSB parameter Λ, which corresponds to the effective supersymmetry breaking scale, is varied from 31 to 510 TeV. It is proportional to the sparticle masses. The range of its values gives a tau slepton mass of 100 to 1600 GeV. Other parameters are fixed to the following values. The number of the messenger SU(5) multiplets $N_{\text{mes}} = 3$ and their mass scale M is set as $M_{\text{mes}}/\Lambda = 2$. The ratio of the vacuum expectation values of the Higgs doublets is $\tan\beta = 10$ and a positive sign of the higgsino mass term, $\mu > 0$, is assumed. The large value of the scale factor of the gravitino coupling, $C_{\text{grav}} = 10000$, results in a long-lived $\tilde{\tau}_1$. The SUSY mass spectrum produced is input to PYTHIA 6.4 [36] with the Z2* tune [44] as the generator for a MC simulation at 13 TeV. Two tau slepton samples are generated for each SUSY point: one with all processes (labeled "GMSB stau”) and one with only direct pair production (labeled “Pair prod. stau”). The pair-produced stau includes only $\widetilde{\tau}_1$, which is predominantly $\widetilde{\tau}_R$ for these model parameters. The *tracker-only* and *tracker+TOF* analyses are both used to search for these signals.

The last type of signal is based on modified Drell–Yan (DY) production of long-lived lepton-like fermions. In this scenario, new massive spin-1/2 particles have arbitrary electric charge but are neutral under $SU(3)_{Colour}$ and $SU(2)_{Left}$, and therefore couple only to the photon and the Z boson. PYTHIA v6.4 [36] with the Z2* tune [44] is used to generate these 13 TeV MC signal samples. Simulations of events with lepton-like fermions are generated with masses ranging from 100 to 2600 GeV and for electric charges $|Q| = 1e$ and $2e$.

Different PYTHIA tunes were studied and the effects on the kinematic distribution were negligible for the HSCPs considered. The *tracker-only* and *tracker+TOF* analyses are both expected to have sensitivity to $|Q| = 2e$ HSCPs.

In all signal samples, simulated minimum bias events are overlaid with the primary collision to produce the effect of additional interactions in the same LHC beam crossing (pileup).

3 The CMS detector

The central feature of the CMS [45] apparatus is a 3.8 T superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Outside the solenoid, forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the projection on the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$.

The silicon tracker, consisting of 1440 silicon pixel and 15 148 silicon strip detector modules , measures charged particles within the pseudorapidity range $|\eta| < 2.5$. Isolated particles of transverse momentum $p_{\mathrm{T}} = 100$ GeV and with $|\eta| < 1.4$ have track resolutions of 2.8% in p_{T} and 10 (30) μm in the transverse (longitudinal) impact parameter [46]. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, using three technologies: drift tubes (DTs), cathode strip chambers (CSCs), and resistive-plate chambers (RPCs). Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_{\mathrm{T}} < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_{T} resolution in the barrel is better than 10% for muons with p_{T} up to 1 TeV [47].

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest within a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [45].

3.1 $\mathrm{d}E/\mathrm{d}x$ measurements

For the reconstructed track, information about $\mathrm{d}E/\mathrm{d}x$ can be gained from measurements of ionization deposited in layers of the pixel and silicon tracker. The ionization charge measured is compared with that expected from a Minimum-Ionizing Particle (MIP), and its level of compatibility can provide a probability, using a $\mathrm{d}E/\mathrm{d}x$ discriminator. As in Ref. [23], to distinguish SM particles from HSCP candidates the I_{as} discriminator is used and is given by

$$I_{as} = \frac{3}{N}\left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i\left(P_i - \frac{2i-1}{2N}\right)^2\right]\right), \tag{1}$$

where N is the number of measurements in the silicon-tracker detectors, P_i is the probability for a MIP to produce a charge smaller or equal to that of the ith measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing P_i.

In addition, the $\mathrm{d}E/\mathrm{d}x$ of a track is estimated using a harmonic-2 estimator:

$$I_{\mathrm{h}} = \left(\frac{1}{N_{85\%}}\sum_{i}^{N_{85\%}} c_i^{-2}\right)^{-1/2}, \tag{2}$$

where c_i is the charge per unit path length in the sensitive part of the silicon detector of the ith track measurement. The harmonic-2 estimator has units MeV/cm and the summation includes just the top 85% of the charge measurements. Ignoring the low charge measurements increases the resilience of the estimator against instrumental biases. This procedure is not necessary for I_{as} which is, by construction, robust against that type of bias.

The mass of a candidate particle can be calculated [26] from its momentum and its I_{h} $\mathrm{d}E/\mathrm{d}x$ estimate, based on the relation:

$$I_{\mathrm{h}} = K\frac{m^2}{p^2} + C, \tag{3}$$

where the empirical parameters $K = 2.684 \pm 0.001\,\mathrm{MeV\,cm^{-1}}$ and $C = 3.375 \pm 0.001\,\mathrm{MeV\,cm}{-1}$ are determined from data using a sample of low-momentum protons. As the momentum reconstruction is done assuming $|Q| = 1e$ particles, Eq. (3) leads to an accurate mass reconstruction only for singly charged particles.

The HSCP candidates are preselected using the I_{as} discriminator because it has a better signal-to-background discriminating power compared to the I_{h} estimator or the mass. Nonetheless, the mass is used at the last stage of the analysis, after the I_{as} selection, to further discriminate between signal and backgrounds since the latter tend to have a low reconstructed mass.

3.2 Time-of-flight measurements

The time-of-flight to the muon system can be used to discriminate between particles travelling at near the speed of light and slower candidates. Both the DT and the CSC muon systems measure the time of each hit. In the DT, the precision position is obtained from this time measurement. The synchronization works in a such a way that a relativistic muon produced at the interaction point gives an aligned pattern of hits in consecutive DT layers. For a slower HSCP particle, hits in each DT layer will be reconstructed as shifted with respect to its true position and will form a zigzag pattern with an offset proportional to the particle delay, δ_t. In the CSC the delay is measured for each hit separately. Each δ_t measurement can be used to determine the track β via the equation:

$$\beta^{-1} = 1 + \frac{c\delta_t}{L} \tag{4}$$

where L is the flight distance. The track β^{-1} value is calculated as the weighted average of the β^{-1} measurements from the DT and CSC systems associated with the track. The weight for the i^{th} DT measurement is given by

$$w_i = \frac{(n-2)}{n}\frac{L_i^2}{\sigma_{\text{DT}}^2} \tag{5}$$

where n is the number of ϕ projection measurements found in the muon chamber producing the measurement and σ_{DT} is the time resolution of the DT measurements, for which the measured value of 3 ns is used. The factor $(n-2)/n$ accounts for residuals computed using the two parameters of a straight line determined from the same n measurements. The minimum number of hits in a given DT chamber that allows for at least one residual calculation is $n = 3$. The weight for the ith CSC measurement is given by

$$w_i = \frac{L_i^2}{\sigma_i^2} \tag{6}$$

where σ_i, the measured time resolution, is 7.0 ns for cathode strip measurements and 8.6 ns for anode wire measurements.

The resolution on the weighted average β^{-1} measurement is approximately 0.065 in both the DT and CSC subsystems.

4 Data selection

All events pass a trigger requiring either a reconstructed muon with high transverse momentum or large $E_{\mathrm{T}}^{\text{miss}}$, calculated using an online particle-flow algorithm [48–50].

The muon trigger is more efficient than the $E_{\mathrm{T}}^{\text{miss}}$ trigger for all HSCP models considered with the exception of the charge-suppressed R-hadron model, but it is not efficient for particles that are slow ($\beta < 0.6$).

The $E_{\mathrm{T}}^{\text{miss}}$ trigger can recover some events in which the HSCP is charged in the tracker and neutral in the muon subsystem. The particle-flow algorithm rejects tracks reconstructed only in the tracker and having a track p_{T} significantly greater than the matched energy deposited in the calorimeter [49], as would be the case for HSCPs that become neutral in the calorimeter. Thus only an HSCP's energy deposit in the calorimeter, roughly 10–20 GeV, will be included in the $E_{\mathrm{T}}^{\text{miss}}$ calculation. Where one or more HSCPs fail to be reconstructed as muon candidates, the events may appear to have significant $E_{\mathrm{T}}^{\text{miss}}$.

For both the *tracker-only* and the *tracker+TOF* analyses, the muon high-level trigger requires a muon candidate with $p_{\mathrm{T}} > 50$ GeV and the $E_{\mathrm{T}}^{\text{miss}}$ trigger requires $E_{\mathrm{T}}^{\text{miss}} > 170$ GeV. Using these two triggers for both analyses allows for increased sensitivity to HSCP candidates that arrive in the muon system very late, as well as for hadron-like HSCPs, which may be charged only in the tracker.

Offline, for the *tracker-only* analysis, all events are required to have a candidate track with $p_{\mathrm{T}} > 55$ GeV as measured in the tracker, relative uncertainty in p_{T} ($\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$) less than 0.25, $|\eta| < 2.1$, and the track fit $\chi^2/\text{dof} < 5$. The magnitudes of the impact parameters d_z and d_{xy} must both be less than 0.5 cm, where d_z and d_{xy} are the longitudinal and transverse impact parameters with respect to the vertex with the smallest d_z. The requirements on the impact parameters are very loose compared to the resolutions for tracks in the tracker. Candidates must pass isolation requirements in the tracker and calorimeter. The tracker isolation criterion is $\sum p_{\mathrm{T}} < 50$ GeV, where the sum is over all tracks (except the candidate) within

$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ of the candidate track. The calorimeter isolation criterion is $E/p = 0.3$, where E is the sum of energy deposited in the calorimeter towers within $\Delta R = 0.3$ and p is the track momentum reconstructed from the tracker. Candidate tracks must have at least two measurements in the silicon pixel detector and at least six measurements in the strip detectors. In addition, there must be measurements in at least 80% of the silicon layers between the first and last measurements of the track. To reduce the contamination from clusters with a large energy deposition due to overlapping tracks, a filtering procedure is applied to remove clusters in the silicon strip tracker that are not consistent with the passage of a singly charged particle (i.e., a narrow cluster with most of the energy deposited in one or two strips). After cluster filtering, there must be at least six measurements in the silicon tracker that are used for the $\mathrm{d}E/\mathrm{d}x$ calculation.

The *tracker+TOF* analysis applies the same criteria, but additionally requires a reconstructed muon matched to the track in the inner detectors. At least eight independent time measurements are needed for the TOF computation. Finally, $1/\beta > 1$ and $\sigma_{1/\beta} < 0.15$ are required.

5 Background estimation

For background estimation we follow the procedure described in our previous work [26]. Candidates passing the preselection (Section 4) are subject to either two or three additional criteria to improve the signal-to-background discrimination. By choosing two uncorrelated criteria it is possible to predict the background using the ABCD (matrix) method. In this approach, the expected background in the signal region, D, is estimated by BC/A, where B and C are the number of candidates that fail the first or second criterion, respectively, while A is the number of candidates that fail both criteria.

Results are based upon a comparison of the number of candidates passing the selection criteria defining the signal region with the number of predicted background events in that region. Fixed selections on the appropriate set of I_{as}, p_{T}, and $1/\beta$ are used to define the final signal region (and the regions for the background prediction). The values are chosen to give the best discovery potential over the signal mass regions of interest.

For the *tracker-only* analysis, the two criteria are $p_{\mathrm{T}} > 65\,\mathrm{GeV}$ and $I_{\mathrm{as}} > 0.3$. The candidates passing only the I_{as} requirement fall into the B region and those passing only the p_{T} requirement fall into the C region. The B and C candidates are then used to form binned probability density functions in I_{h} and p, respectively, such that, using the mass value (Eq. (3)), the full mass spectrum of the background in the signal region D can be predicted. However, the η distribution of candidates with low $\mathrm{d}E/\mathrm{d}x$ differs from the distribution of candidates with high $\mathrm{d}E/\mathrm{d}x$. To correct for this, events in the C region are weighted such that the η distribution matches that in the B region.

For the *tracker+TOF* analysis, a three-dimensional matrix method is used with $p_{\mathrm{T}} > 65\,\mathrm{GeV}$, $I_{\mathrm{as}} > 0.175$, and $1/\beta > 1.25$, creating eight regions labeled A–H. Region D represents the signal region, with events passing all three criteria. The candidates in the A, F, and G regions pass only the $1/\beta$, I_{as}, and p_{T} criteria, respectively, while the candidates in the B, C, and H regions fail only the p_{T}, I_{as}, and $1/\beta$ criteria, respectively. The E region contains events that fail all three criteria. Background estimates can be made from several different combinations of these regions. The combination $D = AGF/E^2$ is used because it yields the smallest statistical uncertainty. As in the *tracker-only* analysis, events in the G region are reweighted to match the η distribution in the B region. The spread in background estimated from the other combinations is less than 20%, which is taken as the systematic uncertainty in the collision background

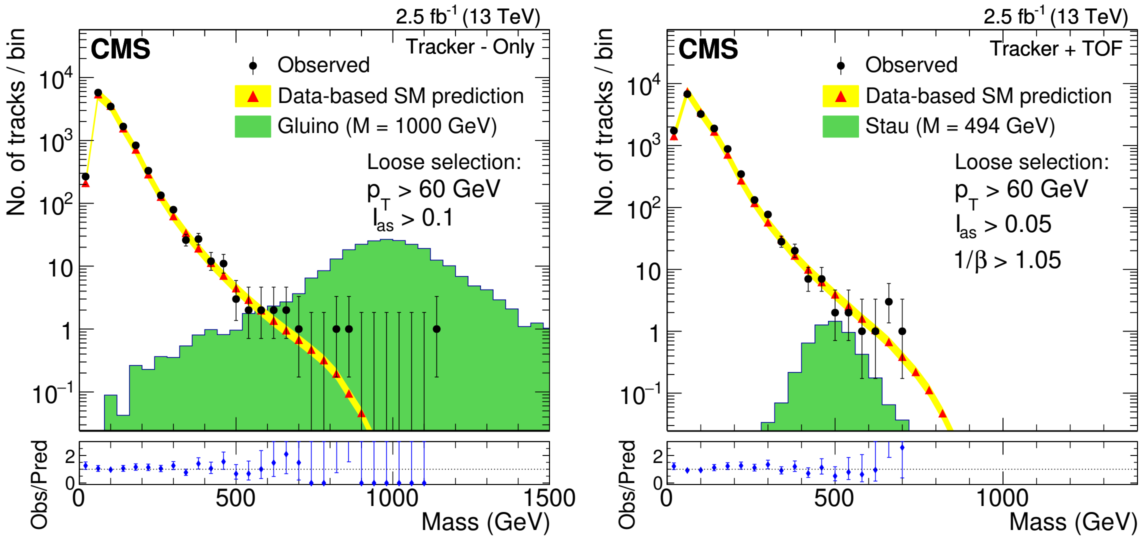

Figure 2: Observed and predicted mass spectra for loose selection candidates in the *tracker-only* (left) and *tracker+TOF* (right) analyses. The expected distributions for representative signals are shown as histograms.

estimate. The same 20% systematic uncertainty is used for the *tracker-only* analysis.

In order to check the background prediction, samples with a loose selection, which would be dominated by background tracks, are used for the *tracker-only* and *tracker+TOF* analyses. The loose selection sample for the *tracker-only* analysis is defined as $p_{\mathrm{T}} > 60\,\mathrm{GeV}$ and $I_{as} > 0.10$. The loose selection sample for the *tracker+TOF* analysis is defined by $p_{\mathrm{T}} > 60\,\mathrm{GeV}$, $I_{as} > 0.05$, and $1/\beta > 1.05$. Figure 2 shows the observed and estimated mass spectra for these samples.

For both analyses, an additional requirement on the reconstructed mass is applied. The specific requirement is adapted to each HSCP model. For a given signal mass and model, the mass requirement is $M \geq M_{\mathrm{reco}} - 2\sigma$, where M_{reco} is the average reconstructed mass for the given mass M_{HSCP} and σ is the expected resolution. Simulation is used to determine M_{reco} and σ.

Table 1 lists the final selection criteria, the predicted number of background events, and the number of events observed in the signal region. Agreement between prediction and observation is seen for both the *tracker-only* and the *tracker+TOF* analyses. Figure 3 shows the predicted and observed mass distributions for the *tracker-only* and the *tracker+TOF* analyses with the final selection.

6 Systematic uncertainties

The sources of systematic uncertainty considered are those related to the background prediction, the signal acceptance, and the integrated luminosity. The uncertainty in the integrated luminosity is 2.7% at $\sqrt{s} = 13\,\mathrm{TeV}$ [51]. The uncertainties in the collision background predictions are estimated to be at the level of 20% for the *tracker-only* and the *tracker+TOF* analyses, as described in Section 5.

The signal acceptance is obtained from MC samples of the various signals processed through the full detector simulation (Section 2). Systematic uncertainties are derived by comparing the response of the detector in the data and simulation. The relevant sources of uncertainty are discussed below.

The signal trigger efficiency is dominated by the muon triggers efficiency, for all the models

Table 1: Selection criteria for the two analyses with the number of predicted and observed events. In the background prediction, the statistical and systematic uncertainties are added in quadrature.

	Selection requirements				Numbers of events $\sqrt{s} = 13\,\text{TeV}$	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
tracker-only	>65	>0.3	—	>0	28.7 ± 6.0	24
				>100	20.7 ± 4.4	15
				>200	3.8 ± 0.8	2
				>300	0.82 ± 0.18	0
				>400	0.25 ± 0.05	0
tracker+TOF	>65	>0.175	>1.250	>0	18.2 ± 3.7	14
				>100	5.4 ± 1.1	4
				>200	0.90 ± 0.19	0
				>300	0.06 ± 0.04	0

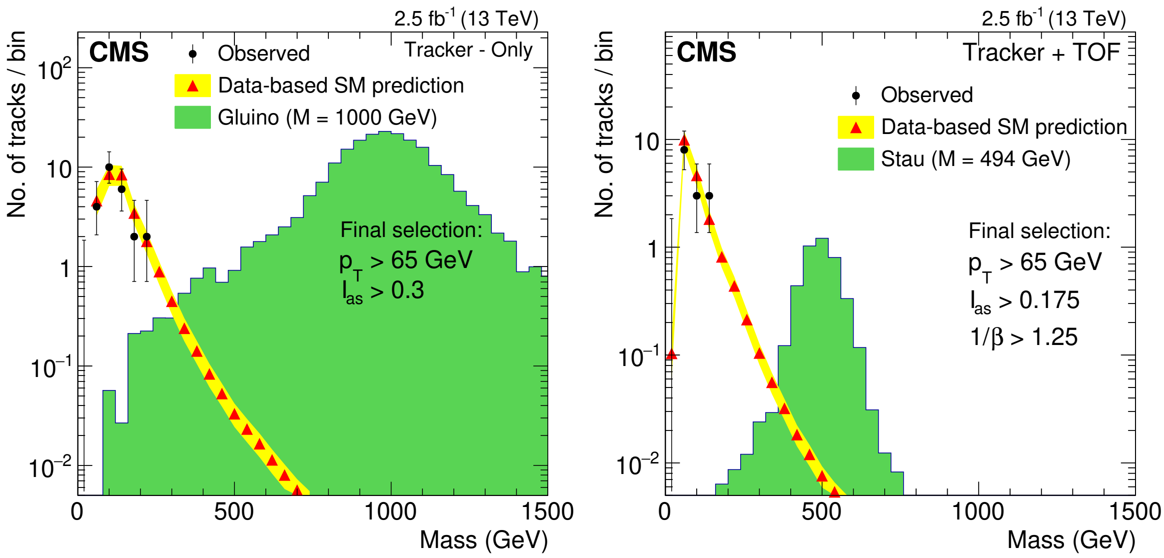

Figure 3: Observed and predicted mass spectra for candidates passing the final selection in the *tracker-only* (left) and *tracker+TOF* (right) analyses. The expected distributions for representative signals are shown as histograms.

except the charge-suppressed ones. The uncertainty in the muon trigger efficiency has many contributions. It is estimated from the difference between the trigger efficiency in data and that seen in simulation, using $Z(\mu\mu)$ data. For genuine muons, the trigger efficiency uncertainty is 3%.

For slow moving particles, the effect of the timing synchronization of the muon system is tested by shifting the arrival times in simulation by the synchronization accuracy observed in data, resulting in an efficiency change of less than 4% for most samples but up to 8% for the 2.4 TeV gluino sample. The uncertainty in the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency is found by varying the jet energy scale in the simulation of the high-level trigger by its uncertainty in data. The $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainty is found to be less than 12% for all samples. The total trigger uncertainty is found to be less than 13% for all the samples, since the muon trigger inefficiencies are often compensated by the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and vice versa.

Low-momentum protons are used to compare the observed and simulated distributions of I_{h} and I_{as} that reflect the energy loss in the silicon tracker. The $\mathrm{d}E/\mathrm{d}x$ distributions of signal samples are varied by the observed differences in order to estimate the systematic uncertainty. The uncertainty in the signal acceptance is usually less than 10%, and is at most 15%.

Bias in the energy loss measurement due to highly ionizing particles (HIP), such as low-momentum protons produced in pp collisions earlier than the triggering collision, was also considered as a source of uncertainty in the I_{h} estimate. In 2015, the LHC collision frequency was doubled, with bunches colliding every 25 ns compared to collisions every 50 ns in 2012, causing an increase of the HIP rate. The contribution of HIPs was included in simulations with the rate observed during the 2015 data taking. The uncertainty in this rate is found to be 25% and 80% for pixel and strip sensors, respectively. Varying the HIP rate in the simulation by these amounts leads to a change in signal acceptance of at most 4% for both analyses.

Dimuon events are used to test the MC simulation of $1/\beta$ by comparing with data. An offset of at most 1.5% is found for the muon system. The resulting uncertainty (labeled "Time-of-flight" in Table 2) in the signal acceptance is found to be less than 5% by shifting $1/\beta$ by this amount.

As in Ref. [25], the uncertainties in the efficiencies for muon [47] and track [52] reconstruction are each less than 2%. The track momentum uncertainty is estimated by shifting the momentum of the inner track, as in Ref. [25]. This uncertainty is found to be less than 5% for most of the samples, increasing to 20% for masses above 2 TeV.

The uncertainty in the number of pileup events is evaluated by varying $\pm 5\%$ the minimum bias cross section used to calculate the weights applied to signal events in order to reproduce the pileup observed in data. The uncertainties due to pileup estimated with this procedure are less than 1%.

The total systematic uncertainty in the signal acceptance is the sum in quadrature of the uncertainties due to the sources discussed above. For almost all signal models, it is less than 20% for both analyses. Only for the *tracker+TOF* analysis of the gluino ($f = 0.5$) sample it is larger, but does not exceed 25%.

Table 2 summarizes the systematic uncertainties for the two analyses. As the uncertainty often depends on the model and HSCP mass, the largest systematic uncertainty is reported for each source.

Table 2: Systematic uncertainties for the two HSCP searches. All values are relative uncertainties in the signal acceptance for the *tracker-only* and *tracker+TOF* analyses.

Source of systematic uncertainty	Relative uncertainty (%)	
Signal acceptance	*tracker-only*	*tracker+TOF*
- Trigger efficiency	13	13
- Track momentum scale	<20	<20
- Track reconstruction	<2	<2
- Ionization energy loss	<15	<15
- HIP background effect	<3	<4
- Time-of-flight	—	<5
- Muon reconstruction	—	2
- Pileup	<1	<1
Tot. uncert. in signal acceptance	<20	<25
Collision background uncert.	20	20
Luminosity uncertainty	2.7	2.7

7 Results

No significant excess of events is observed above the predicted background. Cross section limits are placed at 95% CL using a CL_s approach [53–55] where a profile likelihood technique [56] is used. It utilizes a log-normal model [57, 58] for the nuisance parameters, which are the integrated luminosity, the signal acceptance, and the expected background in the signal region. The observed limits are shown in Fig. 4 for both the *tracker-only* and the *tracker+TOF* analyses along with the theoretical predictions. The theoretical cross sections are computed at NLO or NLO+NLL [59–62] using PROSPINO [63] with CTEQ6.6M PDFs [64]. The uncertainty bands of the theoretical cross sections include the PDF uncertainty, the renormalization and factorization scale uncertainties, and the uncertainty in α_s. The 95% CL limits on the production cross sections are shown in Tables 3, 4, 5, and 6 for long-lived gluino, top squark, tau slepton, and modified Drell–Yan signals, respectively. The limits were determined from the numbers of events passing all final criteria (including the mass criteria).

Mass limits are obtained from the intersection of the observed limit and the central value of the theoretical cross section. The *tracker-only* analysis excludes $f = 0.1$ gluino masses below 1610 (1580) GeV for the cloud interaction model (charge-suppressed model). Top squark masses below 1040 (1000) GeV are excluded for the cloud (charge-suppressed) models. In addition, the *tracker+TOF* analysis excludes $\widetilde{\tau}_1$ masses below 490 (240) GeV for the GMSB (direct pair production) model. Drell–Yan signals with $|Q| = 1e$ ($2e$) are excluded below 550 (680) GeV.

The mass limits obtained at $\sqrt{s} = 13$ TeV for various HSCP signal models are summarized in Table 7 and compared with earlier results at $\sqrt{s} = 7$ and 8 TeV [26]. A significant increase in mass limit is obtained for all models with large QCD production cross section (gluinos, top squarks, and inclusive production of GMSB tau sleptons), arising from the higher center-of-mass energy pp collisions delivered by the LHC. For scenarios with much smaller cross-sections, directly pair-produced tau sleptons and Drell–Yan signals with $|Q| = 1e$, the results do not improve, because the larger integrated luminosity at 7 and 8 TeV with respect to that at 13 TeV prevails over the effect of the increase of the centre-of-mass energy. For the $|Q| = 2e$ analysis, results from the previous analysis optimized for multiply charged signals [26] are also provided.

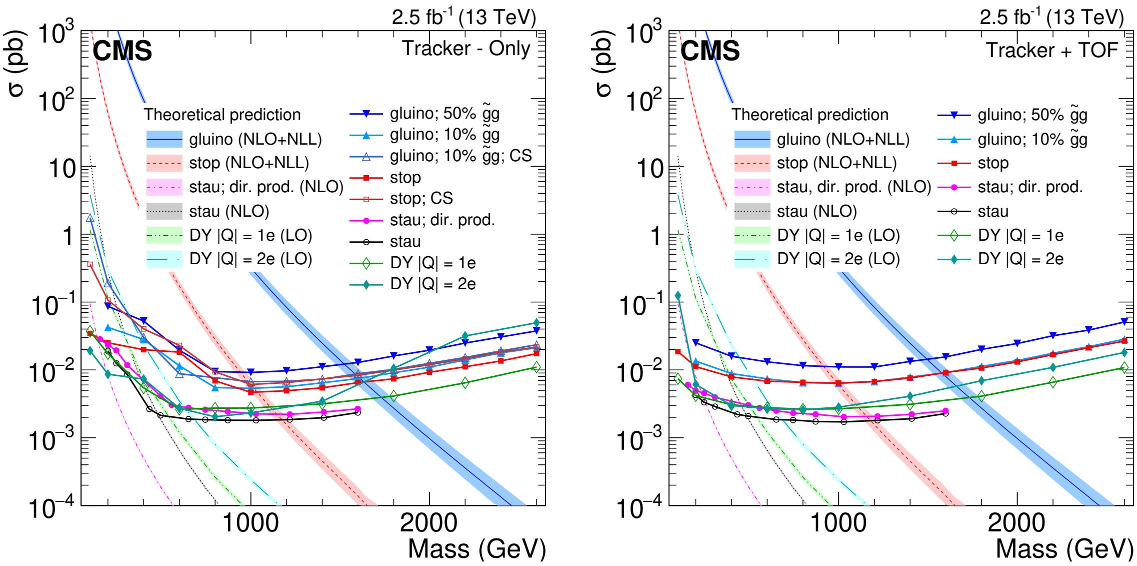

Figure 4: Results of the HSCP search as the cross section upper limits at 95% CL for various signal models for the *tracker-only* analysis (left) and *tracker+TOF* analysis (right) at $\sqrt{s} = 13\,\text{TeV}$. In the legend, "CS" stands for charge-suppressed interaction model.

8 Summary

A search for heavy stable charged particles produced in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ using the CMS detector is presented. Two complementary analyses were performed: using only the tracker and using both the tracker and the muon system. The data are found to be compatible with the expected background. Mass limits for long-lived gluinos, top squarks, tau sleptons, and multiply charged particles are calculated. The models for R-hadron-like HSCPs include a varying fraction of $\tilde{g}$-gluon hadronization and two different interaction models leading to a variety of exotic experimental signatures. The limits are significantly improved over those from Run 1 of the LHC, and the limits on long-lived gluinos, ranging up to 1610 GeV, are the most stringent to date.

Table 3: Summary of the search for long-lived gluinos: the p_T (GeV), I_{as}, $1/\beta$, and mass thresholds M (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass	Requirements				Yields		Signal	σ (pb)		
(GeV)	p_T	I_{as}	$1/\beta$	M	SM predicted	data	eff.	theo.	exp.	obs.
Gluino ($f = 0.1$) with the *tracker-only* analysis										
400	65	0.3	—	60	28.000 ± 5.880	23	0.167	$9.5\times10^{+1}$	3.7×10^{-2}	2.8×10^{-2}
800	65	0.3	—	350	0.435 ± 0.093	0	0.223	1.5	5.5×10^{-3}	5.5×10^{-3}
1200	65	0.3	—	590	0.046 ± 0.010	0	0.220	8.4×10^{-2}	5.6×10^{-3}	5.6×10^{-3}
1600	65	0.3	—	720	0.017 ± 0.004	0	0.166	8.0×10^{-3}	7.5×10^{-3}	7.5×10^{-3}
2000	65	0.3	—	770	0.012 ± 0.003	0	0.112	9.7×10^{-4}	1.1×10^{-2}	1.1×10^{-2}
2400	65	0.3	—	800	0.012 ± 0.002	0	0.072	1.3×10^{-4}	1.8×10^{-2}	1.8×10^{-2}
Gluino charge-suppressed ($f = 0.1$) with the *tracker-only* analysis										
400	65	0.3	—	120	15.600 ± 3.300	10	0.092	$9.5\times10^{+1}$	4.9×10^{-2}	3.0×10^{-2}
600	65	0.3	—	250	1.690 ± 0.369	0	0.141	9.1	1.2×10^{-2}	8.8×10^{-3}
1200	65	0.3	—	580	0.050 ± 0.011	0	0.183	8.4×10^{-2}	6.8×10^{-3}	6.8×10^{-3}
1600	65	0.3	—	680	0.023 ± 0.005	0	0.142	8.0×10^{-3}	8.8×10^{-3}	8.8×10^{-3}
2000	65	0.3	—	670	0.024 ± 0.005	0	0.099	9.7×10^{-4}	1.3×10^{-2}	1.3×10^{-2}
2400	65	0.3	—	680	0.023 ± 0.005	0	0.066	1.3×10^{-4}	1.9×10^{-2}	1.9×10^{-2}
Gluino ($f = 0.5$) with the *tracker-only* analysis										
400	65	0.3	—	50	28.700 ± 6.030	24	0.094	$9.5\times10^{+1}$	6.6×10^{-2}	5.2×10^{-2}
800	65	0.3	—	340	0.491 ± 0.105	0	0.129	1.5	9.5×10^{-3}	9.5×10^{-3}
1200	65	0.3	—	580	0.050 ± 0.011	0	0.127	8.4×10^{-2}	9.7×10^{-3}	9.7×10^{-3}
1600	65	0.3	—	710	0.018 ± 0.004	0	0.096	8.0×10^{-3}	1.3×10^{-2}	1.3×10^{-2}
2000	65	0.3	—	760	0.013 ± 0.003	0	0.063	9.7×10^{-4}	2.0×10^{-2}	2.0×10^{-2}
2400	65	0.3	—	740	0.014 ± 0.003	0	0.040	1.3×10^{-4}	3.1×10^{-2}	3.1×10^{-2}

Table 4: Summary of the search for long-lived top squarks: the p_T (GeV), I_{as}, $1/\beta$, and mass thresholds M (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass	Requirements				Yields		Signal	σ (pb)		
(GeV)	p_T	I_{as}	$1/\beta$	M	SM predicted	data	eff.	theo.	exp.	obs.
Top squark with the *tracker-only* analysis										
200	65	0.3	—	0	28.700 ± 6.030	24	0.195	$6.1\times10^{+1}$	3.3×10^{-2}	2.5×10^{-2}
600	65	0.3	—	40	28.700 ± 6.030	24	0.266	1.7×10^{-1}	2.4×10^{-2}	1.8×10^{-2}
1000	65	0.3	—	320	0.632 ± 0.136	0	0.260	6.0×10^{-3}	4.7×10^{-3}	4.7×10^{-3}
1800	65	0.3	—	660	0.026 ± 0.006	0	0.163	4.6×10^{-5}	7.4×10^{-3}	7.4×10^{-3}
2200	65	0.3	—	690	0.021 ± 0.005	0	0.109	6.0×10^{-6}	1.1×10^{-2}	1.1×10^{-2}
Top squark charge-suppressed with the *tracker-only* analysis										
200	65	0.3	—	0	28.700 ± 6.030	24	0.046	$6.1\times10^{+1}$	1.4×10^{-1}	1.1×10^{-1}
600	65	0.3	—	90	22.500 ± 4.710	16	0.169	1.7×10^{-1}	3.1×10^{-2}	2.3×10^{-2}
1000	65	0.3	—	320	0.632 ± 0.136	0	0.195	6.0×10^{-3}	7.4×10^{-3}	6.1×10^{-3}
1800	65	0.3	—	550	0.063 ± 0.014	0	0.124	4.6×10^{-5}	9.9×10^{-3}	9.9×10^{-3}
2200	65	0.3	—	580	0.050 ± 0.011	0	0.087	6.0×10^{-6}	1.5×10^{-2}	1.5×10^{-2}

Table 5: Summary of the search for long-lived tau sleptons: the p_T (GeV), I_{as}, $1/\beta$, and mass thresholds M (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass	Requirements				Yields		Signal	σ (pb)		
(GeV)	p_T	I_{as}	$1/\beta$	M	SM predicted	data	eff.	theo.	exp.	obs.
Inclusive tau slepton with the *tracker+TOF* analysis										
200	65	0.175	1.25	50	0.861 ± 0.174	0	0.290	2.8×10^{-1}	6.0×10^{-3}	4.3×10^{-3}
308	65	0.175	1.25	130	0.081 ± 0.016	0	0.431	2.5×10^{-2}	2.9×10^{-3}	2.9×10^{-3}
494	65	0.175	1.25	260	0.008 ± 0.002	0	0.592	1.9×10^{-3}	2.1×10^{-3}	2.1×10^{-3}
651	65	0.175	1.25	380	0.002 ± 0.000	0	0.662	4.1×10^{-4}	1.9×10^{-3}	1.9×10^{-3}
1029	65	0.175	1.25	610	0.000 ± 0.000	0	0.710	2.2×10^{-5}	1.7×10^{-3}	1.7×10^{-3}
1599	65	0.175	1.25	910	0.000 ± 0.000	0	0.549	1.0×10^{-6}	2.3×10^{-3}	2.3×10^{-3}
Direct pair prod. of tau slepton with the *tracker+TOF* analysis										
200	65	0.175	1.25	40	0.924 ± 0.187	0	0.242	8.0×10^{-3}	7.1×10^{-3}	4.9×10^{-3}
308	65	0.175	1.25	110	0.130 ± 0.026	0	0.315	1.5×10^{-3}	3.9×10^{-3}	3.9×10^{-3}
494	65	0.175	1.25	230	0.013 ± 0.003	0	0.415	1.9×10^{-4}	3.0×10^{-3}	3.0×10^{-3}
651	65	0.175	1.25	330	0.003 ± 0.001	0	0.496	4.9×10^{-5}	2.5×10^{-3}	2.5×10^{-3}
1029	65	0.175	1.25	590	0.000 ± 0.000	0	0.592	4.0×10^{-6}	2.0×10^{-3}	2.0×10^{-3}
1599	65	0.175	1.25	930	0.000 ± 0.000	0	0.504	0.0	2.5×10^{-3}	2.5×10^{-3}

Table 6: Summary of the search for long-lived particles from modified Drell–Yan models of various charge: the p_T (GeV), I_{as}, $1/\beta$, and mass thresholds M (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass	Requirements				Yields		Signal	σ (pb)		
(GeV)	p_T	I_{as}	$1/\beta$	M	SM predicted	data	eff.	theo.	exp.	obs.
Modified Drell–Yan $\lvert Q\rvert = 1e$ particles with the *tracker+TOF* analysis										
200	65	0.175	1.25	80	0.319 ± 0.065	0	0.303	1.1×10^{-1}	4.2×10^{-3}	4.2×10^{-3}
400	65	0.175	1.25	210	0.018 ± 0.004	0	0.417	7.3×10^{-3}	3.1×10^{-3}	3.1×10^{-3}
600	65	0.175	1.25	350	0.002 ± 0.000	0	0.461	1.2×10^{-3}	2.8×10^{-3}	2.8×10^{-3}
800	65	0.175	1.25	480	0.001 ± 0.000	0	0.485	2.6×10^{-4}	2.6×10^{-3}	2.6×10^{-3}
1000	65	0.175	1.25	610	0.000 ± 0.000	0	0.485	7.6×10^{-5}	2.7×10^{-3}	2.7×10^{-3}
1800	65	0.175	1.25	1020	0.000 ± 0.000	0	0.312	1.0×10^{-6}	4.1×10^{-3}	4.1×10^{-3}
2600	65	0.175	1.25	1270	0.000 ± 0.000	0	0.114	0.0	1.1×10^{-2}	1.1×10^{-2}
Modified Drell–Yan $\lvert Q\rvert = 2e$ particles with the *tracker+TOF* analysis										
200	65	0.175	1.25	0	0.930 ± 0.188	0	0.212	3.0×10^{-1}	8.0×10^{-3}	6.1×10^{-3}
400	65	0.175	1.25	90	0.230 ± 0.047	0	0.409	2.3×10^{-2}	3.0×10^{-3}	3.0×10^{-3}
600	65	0.175	1.25	200	0.021 ± 0.004	0	0.481	3.5×10^{-3}	2.7×10^{-3}	2.7×10^{-3}
800	65	0.175	1.25	300	0.004 ± 0.001	0	0.487	8.0×10^{-4}	2.6×10^{-3}	2.6×10^{-3}
1000	65	0.175	1.25	360	0.002 ± 0.000	0	0.449	2.4×10^{-4}	2.8×10^{-3}	2.8×10^{-3}
1800	65	0.175	1.25	410	0.001 ± 0.000	0	0.182	4.0×10^{-6}	6.9×10^{-3}	6.9×10^{-3}
2600	65	0.175	1.25	480	0.001 ± 0.000	0	0.069	0.0	1.8×10^{-2}	1.8×10^{-2}

Table 7: Mass limits obtained at $\sqrt{s} = 13\,\text{TeV}$ for various HSCP candidate models compared with earlier results for $\sqrt{s} = 7 + 8\,\text{TeV}$ [26]. In the model name, "CS" stands for charged suppressed interaction model and "DY" for Drell–Yan. The limits for doubly charged particles are also compared to the earlier CMS results obtained with the '*multiply charged*' analysis, which was specifically designed to search for multiply charged particles.

Model	analysis used	$\sqrt{s} = 7 + 8$ TeV	$\sqrt{s} = 13$ TeV
Gluino $f = 0.1$	*tracker-only*	$M > 1320\,\text{GeV}$	$M > 1610\,\text{GeV}$
	tracker+TOF	$M > 1290\,\text{GeV}$	$M > 1580\,\text{GeV}$
Gluino $f = 0.1$ CS	*tracker-only*	$M > 1230\,\text{GeV}$	$M > 1580\,\text{GeV}$
Gluino $f = 0.5$	*tracker-only*	$M > 1250\,\text{GeV}$	$M > 1520\,\text{GeV}$
	tracker+TOF	$M > 1220\,\text{GeV}$	$M > 1490\,\text{GeV}$
Gluino $f = 0.5$ CS	*tracker-only*	$M > 1150\,\text{GeV}$	$M > 1540\,\text{GeV}$
Top squark	*tracker-only*	$M > 930\,\text{GeV}$	$M > 1040\,\text{GeV}$
	tracker+TOF	$M > 910\,\text{GeV}$	$M > 990\,\text{GeV}$
Top squark CS	*tracker-only*	$M > 810\,\text{GeV}$	$M > 1000\,\text{GeV}$
GMSB tau slepton	*tracker+TOF*	$M > 430\,\text{GeV}$	$M > 490\,\text{GeV}$
	tracker-only	$M > 389\,\text{GeV}$	$M > 480\,\text{GeV}$
Pair prod. tau slepton	*tracker+TOF*	$M > 330\,\text{GeV}$	$M > 240\,\text{GeV}$
	tracker-only	$M > 180\,\text{GeV}$	—
DY $\lvert Q \rvert = 1e$	*tracker-only*	$M > 640\,\text{GeV}$	$M > 510\,\text{GeV}$
	tracker+TOF	$M > 650\,\text{GeV}$	$M > 550\,\text{GeV}$
DY $\lvert Q \rvert = 2e$	*multiply charged*	$M > 720\,\text{GeV}$	—
	tracker-only	$M > 520\,\text{GeV}$	$M > 680\,\text{GeV}$
	tracker+TOF	$M > 520\,\text{GeV}$	$M > 660\,\text{GeV}$

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